Frascati Physics Series Vol. nnn (2001), pp. 000-000
PIC 2001 - Seoul, June, 2001

THE HIGHEST ENERGY PARTICLES IN THE UNIVERSE: THE MYSTERY AND ITS POSSIBLE SOLUTIONS

Pasquale Blasi
Osservatorio Astrofisico di Arcetri, Largo E. Fermi, 5 - Firenze (ITALY)

ABSTRACT

The universe should be dark at energies exceeding $\sim 5 \times 10^{19}$ eV. This simple but solid prediction of our best known particle physics is not confirmed by observations, that seem to suggest a quite different picture. Numerous events have in fact been detected in this energy region, with spectra and anisotropy features that defy many conventional and unconventional explanations. Is there a problem with known physics or is this a result of astrophysical uncertainties? Here we try to answer these questions, in the light of present observations, while discussing which information future observations may provide on this puzzling issue.

1 Introduction

One of the major goals of cosmic ray physics has always been the discovery and understanding of the *end of the cosmic ray spectrum*. Until the end of the '60s,

this search was mainly aimed to understand the limits to the acceleration processes and nature of the sources responsible for the production of the particles with the highest energies. However, after the discovery of the cosmic microwave background (CMB), it became soon clear that the observed spectrum of the cosmic radiation had to be cut off at a "natural" energy, even if an ideal class of sources existed, able to accelerate particles to infinite energy. In fact, if the sources are distributed homogenously in the universe, the photopion production in the scattering of particles off the CMB photons imply a cutoff in the observed spectrum of the cosmic rays at an energy $E_{GZK} \sim (4-5) \times 10^{19}$ eV, close to the kinematic threshold for that process [1]. This cutoff has become known as the *GZK cutoff* and particles with $E > E_{GZK}$ are usually named ultra-high energy cosmic rays (UHECRs).

Several experiments have been operating to detect the flux of UHECRs, starting with Volcano Ranch [2] and continuing with Haverah Park [3] and Yakutsk [4] to the more recent experiments like AGASA [5, 6, 7, 8], Fly's Eye [9, 10, 11] and HiRes [12]. The search for the GZK cutoff, instead of confirming the simple picture illustrated above, has provided stronger and stronger evidence for the existence of events corresponding to energies well in excess of E_{GZK}: the GZK cutoff has not been found.

This problem hides many issues on plasma physics, particle physics and astrophysics, that in their whole represent the puzzle of UHECRs. In section 2 the present status of observations of UHECRs is summarized; in section 3 some caveats in the arguments that are often used to address the problem of UHECRs are considered, for the purpose of stating the problem in a clear way. In sections 4.1 and 4.2 the bottom-up and top-down models of UHECR origin are summarized. In section 5 some speculations are discussed of new physics scenarios that might play a role not only for the explanation of UHECRs, but also for the understanding of other current puzzles in high energy astrophysics. Conclusions are reported in section 6.

2 Observations

The cosmic ray spectrum is measured from fractions of GeV to a (current) maximum energy of 3×10^{20} eV. The spectrum above a few GeV and up to $\sim 10^{15}$ eV (the knee) is measured to be a power law with slope ~ 2.7, while at higher energies and up to $\sim 10^{19}$ eV (the ankle) the spectrum has a steeper

slope, of ~ 3.1. At energy larger than 10^{19} eV a flattening seems to be present.

The statistics of events is changing continuously: the latest analysis of the "all experiments" statistics was carried out in [13] where 92 events were found above 4×10^{19} eV. 47 events were detected by the AGASA experiment. A more recent analysis [5] of the AGASA data, carried out expanding the acceptance angle to $\sim 60^o$, has increased the number of events in this energy region to 59.

In [6] the directions of arrival of the AGASA events (with zenith angle smaller than 45^o) above 4×10^{19} eV were studied in detail: no appreciable departure from isotropy was found, with the exception of a few small scale anisotropies in the form of doublets and triplets of events within an angular scale comparable with the angular resolution of the experiments ($\sim 2.5^o$ for AGASA). This analysis was repeated in [13] for the whole sample of events above 4×10^{19} eV, and a total of 12 doublets and 3 triplets were found within $\sim 3^o$ angular scales. The attempt to associate these multiplets with different types of local astrophysical sources possibly clustered in the local supercluster did not provide evidence in that direction [14].

Recently, the AGASA collaboration reported on the study of the small scale anisotropies in the extended sample of events with zenith angle $< 60^o$: 5 doublets (chance probability $\sim 0.1\%$) and 1 triplet (chance probability $\sim 1\%$) were found.

The information available on the composition of cosmic rays at the highest energies is quite poor. A study of the shower development was possible only for the Fly's Eye event [11] and disfavors a photon primary [15]. A reliable analysis of the composition is however possible only on statistical basis, because of the large fluctuations in the shower development at fixed type of primary particle.

The Fly's Eye collaboration reports of a predominantly heavy composition at 3×10^{17} eV, with a smooth transition to light composition at $\sim 10^{19}$ eV. This trend was later not confirmed by AGASA [8, 16].

Recently in ref. [17] the data of the Haverah Park experiment on highly inclined events were re-analyzed: this new analysis results in no more than 30% of the events with energy above 10^{19} eV being consistent with photons or iron (at 95% confidence level) and no more than 55% of events being photons above 4×10^{19} eV.

Recently a new mass of data has been presented by the HiRes experiment

[18]. Only two events with energy above 10^{20} eV have been detected by this experiment insofar, compatible with the presence of a GZK cutoff. This discrepancy with the results of several years of AGASA operation needs further investigation. Several sistematics have been identified that might considerably affect the determination of the energies and fluxes of fluorescence experiments versus the ground array techniques [5]. These issues will not be discussed further in the present paper.

3 The GZK cutoff: how serious is its absence?

The puzzle of UHECRs can be summarized in the following points:

- *The production problem:* the generation of particles of energy $\geq 10^{20}$ eV requires an excellent accelerator, or some new piece of physics that allows the production of these particles in a non-acceleration scenario.

- *The large scale isotropy:* observations show a remarkable large scale isotropy of the arrival directions of UHECRs, with no correlation with local structures (e.g. galactic disk, local supercluster, local group).

- *The small scale anisotropy:* the small (degree) scale anisotropies, if confirmed by further upcoming experiments, would represent an extremely strong constraint on the type of sources of UHECRs and on magnetic fields in the propagation volume.

- *The GZK feature:* the GZK cutoff is mainly a geometrical effect: the number of sources within a distance that equals the pathlength for photopion production is far less than the sources that contribute lower energy particles, having much larger pathlength (comparable with the size of the universe). The crucial point is that the cutoff is present even if plausible nearby UHECR engines are identified.

- *The composition:* it is crucial to determine the type of particles that generate the events at ultra-high energies. The composition can be really considered a smoking gun either in favor or against whole classes of models.

The five points listed above are most likely an oversimplification of the problem: some other issues could be added to the list, such as the spectrum,

but at least at present this cannot be considered as a severe constraint. On the other hand, specific models make specific predictions on the spectral shape, so that when the results of future observations will be available, this information will allow a strong discrimination among different explanations for the origin of UHECRs. Any model that aims to the explanation of the problem of UHECRs must address all of the issues listed above (and possibly others).

In this section we consider in some more detail the issue of the GZK cutoff and the seriousness of its absence in the observed data.

It is often believed that the identification of one or a class of nearby UHECR sources would explain the observations and in particular the absence of the GZK cutoff. This is not necessarily true. The (inverse of the) lifetime of a proton with energy E is plotted in fig. 1 (left panel) together with the derivative with respect to energy of the rate of energy losses $b(E)$ (right panel) [the figure has been taken from ref. [19)]]. The flux per unit solid angle at energy E in some direction is proportional to $n_0\lambda(E)\Phi(E)$, where n_0 is the density of sources (assumed constant), $\lambda(E) = c/((1/E)dE/dt)$ and $\Phi(E)$ is the source spectrum. This rough estimate suggests that the ratio of detected fluxes (multiplied as usual by E^3), at energies E_1 and E_2 is

$$\mathcal{R} = \frac{E_1^3 F(E_1)}{E_2^3 F(E_2)} \sim \frac{\lambda(E_1)\Phi(E_1)E_1^3}{\lambda(E_2)\Phi(E_2)E_2^3} = \frac{\lambda(E_1)}{\lambda(E_2)}\left(\frac{E_1}{E_2}\right)^{3-\gamma}, \qquad (1)$$

where in the last term we assumed that the source spectrum is a power law $\Phi(E) \sim E^{-\gamma}$. If for instance one takes $E_1 = 10^{19}$ eV (below E_{GZK}) and $E_2 = 3\times10^{20}$ eV (above E_{GZK}), from fig. 1 one obtains that $\mathcal{R} \sim 80$ for $\gamma = 3$ and $\mathcal{R} \sim 10$ for $\gamma = 2.4$. The ratio $\mathcal{R}$ gives a rough estimate of the suppression factor at the GZK cutoff and its dependence on the spectrum of the source. For flat spectra ($\gamma \leq 2$) the cutoff is less significant, but it is more difficult to fit the low energy data [20)] (at $E \sim 10^{19}$ eV). Steeper spectra make the GZK cutoff more evident, although they allow an easier fit of the low energy data. The simple argument illustrated above can also be interpreted in an alternative way: if there is a local overdensity of sources by a factor $\sim \mathcal{R}$, the GZK cutoff is attenuated with respect to the case of homogeneous distribution of the sources. The question of whether we are located in such a large overdensity of sources was recently addressed, together with the propagation of UHECRs, in [20)]. Assuming that the density of the (unknown) sources follows the density of galaxies in large scale structure surveys like PSCz [23)] and Cfa2 [24)], the

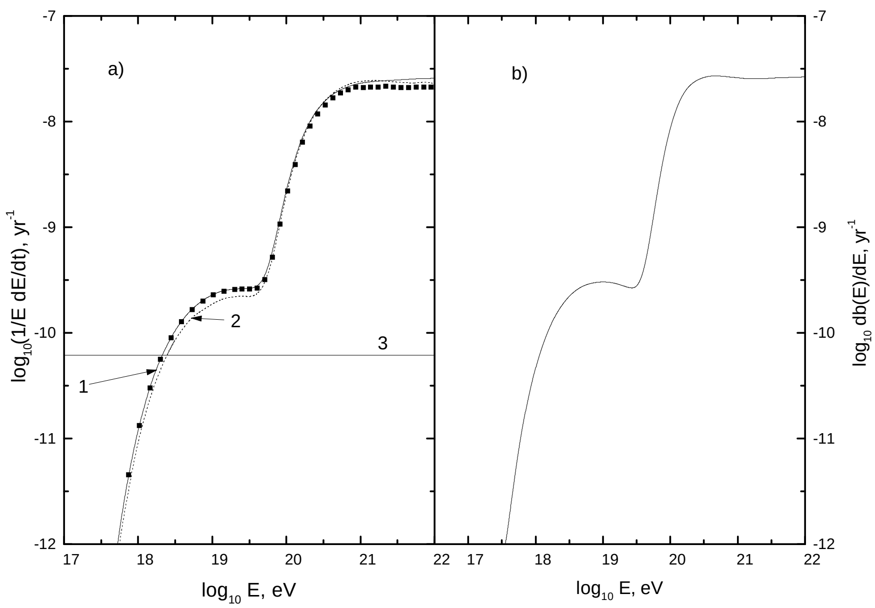

Figure 1: *From* [19]*. Left panel)* $(1/E)dE/dt$ *for a proton in* [19] *(curve 1), in* [21] *(curve 2) and in* [22] *(black squares). The curve 3 is the contribution of the red shift. Right panel) The derivative* $db(E)/dE$*, with* $b(E) = dE/dt$ *at* $z = 0$*.*

authors estimate the local overdensity on scales of several Mpc to be of order ~ 2, too small to compensate for the energy losses of particles with energy above the threshold for photopion production.

There is however another issue that the calculations in [20] address, which is related to the statistical fluctuations induced by the process of photopion production. The large inelasticity of this process can be taken into account properly only through the use of Montecarlo calculations. When the Montecarlo is applied to simulate the small statistics of events typical of current experiments, the fluctuations in the simulated fluxes above $\sim 10^{20}$ eV are very large, so that for flat spectra ($\sim E^{-2}$) the discrepancy between observations and simulations on the total number of events above $\sim 10^{20}$ eV is at the level of $\sim 2\sigma$ (in agreement with the conclusions of Ref. [25]). The situation is represented in fig. 2 [20] where the hatched regions show the uncertainties in the simulated fluxes. The data points are from AGASA [7, 26]. The bottom line of this section can be summarized in the following few points:

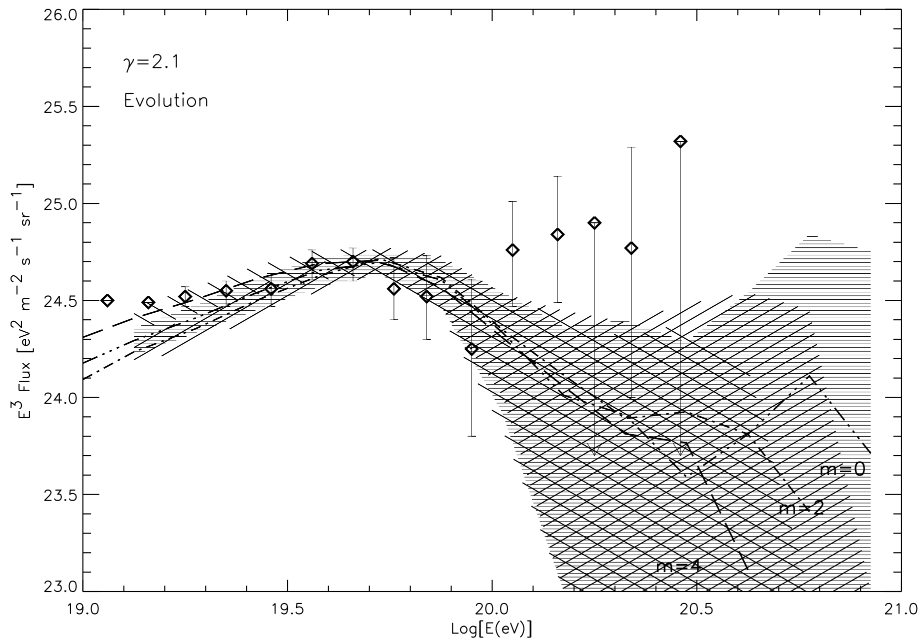

Figure 2: *Simulated fluxes with the AGASA statistics and* $\gamma = 2.1$*. The sources are homogeneously distributed up to a maximum redshift* $z_{max} = 1$*. The different hatches refer to different cases of evolution of the sources* [20]*.*

1) the GZK cutoff is not avoided by finding sources of UHECRs that lie within the pathlength of photopion production, unless these sources are located only or predominantly nearby and are less abundant at large distances.

2) The significance of the GZK feature depends on the fluctuations in the photopion production, and can be addressed properly only with a enhanced statistics of events with energy $\geq 10^{20}$ eV.

4 The UHECRs engines

Models for the origin of UHECRs can be strongly constrained on the basis on the criteria illustrated in the previous section. The challenge to conventional acceleration models, that are supposed to work at lower energy scales, induced an increasing interest for more exotic generation mechanisms, eventually requiring new particle physics. In this section the main ideas on production scenarios and their signatures will be summarized.

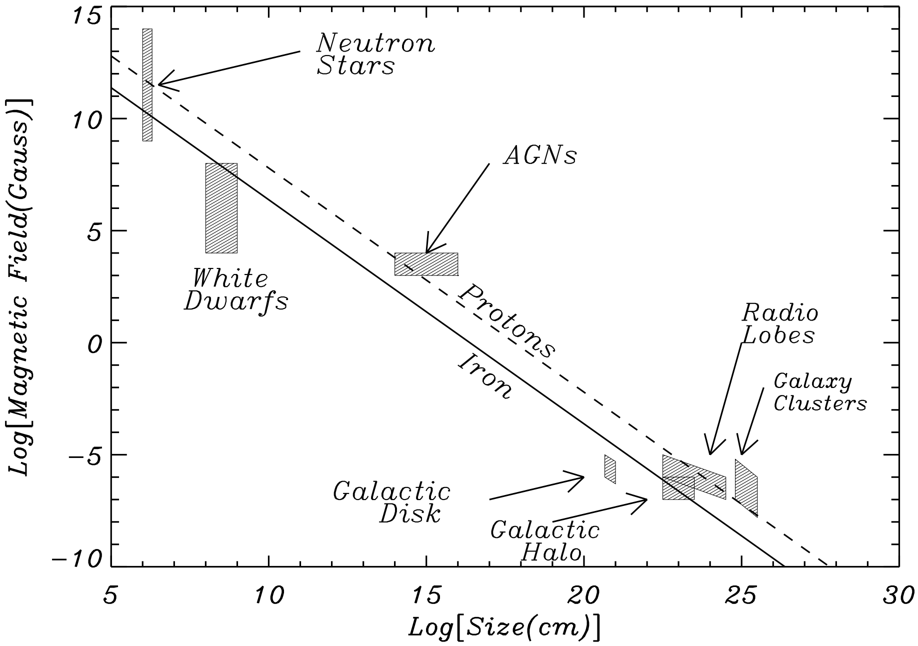

Figure 3: *The Hillas Plot.*

4.1 Acceleration scenarios: the physics of Zevatrons

The accelerators able to reach maximum energies of order 1 ZeV have been named Zevatrons [27]. The challenge for Zevatrons was recently discussed in detail by several authors [28, 27]: the main concept in this class of models is that the energy flux embedded in a macroscopic motion or in magnetic fields is partly converted into energy of a few very high energy particles. This is what happens for instance in shock acceleration.

A discussion of all the models in the literature is not the purpose of the present paper, and in a sense we think it may not be very interesting. Nevertheless, it is instructive to understand at least which classes of models may have a chance to explain the acceleration to ZeV energies. In this respect, a pictorial way of proceeding is based on what is known as the Hillas plot [29]. Our version of it is reported in fig. 4.

In the Hillas plot the maximum energy is taken to be in its simplest form, as determined by the local magnetic field B and the size L of the accelerator: $E_{max} = ZeBL$. Here Ze is the electric charge of the accelerated particles. From fig. 4 it is evident that only 4 classes of sources have the potential to accelerate protons to ultra-high energies: 1) Neutron stars; 2) Radio Lobes;

3) Active Galactic Nuclei; 4) Clusters of Galaxies. In the case of Iron, the situation becomes more promising for other sources, like the galactic halo or extreme white dwarfs. These sources would however have other problems that make them unlikely sources of UHECRs.

The hillas plot does not include the effect of energy losses in the acceleration sites. Photopion production limits the maximum energy achievable in clusters of galaxies to $\leq$ a few 10^{19} eV. These sources will therefore not be considered any longer as sources of cosmic rays above the GZK energy. We also do not discuss here the so-called bursting sources. The prototypical example of these sources are gamma ray bursts, that have been proposed as sources of UHECRs [30]. We refer the reader to recent literature treating this topic [31].

In the following we briefly summarize the situation with the other three classes of objects listed above.

<u>*Neutron Stars*</u>

The possibility that neutron stars may be accelerators of UHECRs was discussed in detail in Ref. [32] (and references therein). The main problem encountered in reaching the highest energies is related to the severe energy losses experienced by the particles in the acceleration site [33, 32]. Most of the mechanisms discussed in the literature refer to acceleration processes in the magnetosphere of the neutron star, where curvature radiation limits the maximum energy to a value much smaller that 10^{20} eV.

An alternative approach is to think of acceleration processes that occur outside the light cylinder of young neutron stars [34, 35].

Rapidly rotating, newly formed neutron stars can induce the acceleration of iron nuclei through MHD winds outside the light cylinder [34]. Although the mechanism through which the rotation energy of the star is converted into kinetic energy of the wind is not yet completely understood, it seems from the observations of the Crab nebula that a relativistic wind does indeed exist, with a Lorentz factor of $\sim 10^7$ [36]. Possible nuclei with charge $Z_{26} = Z/26$ can be accelerated in young neutron stars to a maximum energy $E_{max} = 8 \times 10^{20} Z_{26} B_{13} \Omega_{3k}^2$, as estimated in Ref. [34]. Here B_{13} is the surface magnetic field in units of 10^{13} G and $\Omega_{3k} = \Omega/3000\mathrm{s}^{-1}$ is the rotation frequency of the star. Energies gradually smaller are produced while the star is spinning down, so that a spectrum $\sim E^{-1}$ is produced by a neutron star. The process of escape of the accelerated particles becomes efficient about a year after the neutron star

birth. Particles that are generated earlier cannot escape, but can produce high energy neutrinos in collisions with the ambient particles and photons [37]. The issue of the anisotropy due to the galactic disk is currently under investigation [38].

Active Galactic Nuclei

Active galaxies are thought to be powered by the accretion of gas onto supermassive black holes. Acceleration of particles can occur in standing shocks in the infalling gas or by unipolar induction in the rotating magnetized accretion disk [39]. In the former scenario energy losses and size of the acceleration region are likely to limit the maximum energy of the accelerated particles to $\ll 10^{20}$ eV. In the latter case, the main limiting factor in reaching the highest energies is represented by curvature energy losses, that are particularly severe [32] unless moderately high magnetic fields can be kept with a small accretion rate. This may be the case of dormant supermassive black holes, possibly related to the so-called dark massive objects (DMO). Some 32 of these objects have been identified in a recent survey [40] and 14 of them have been estimated to have the right features for acceleration of UHECRs [41]. Had this model to be right, it would not be suprising that bright counterparts to the UHECR events were not found, since DMOs are in a quiescent stage of their evolution.

Very little is known of DMOs as cosmic ray accelerators: the spectrum is not known, and neither is known their spatial distribution. It is therefore hard to say at present whether DMOs can satisfy the criteria listed in section 3. In [42] an interesting prediction was proposed: if UHECRs are accelerated by unipolar induction, they have to radiate part of their energy by synchrotron emission, resulting in the sources to become observable at TeV energies.

Jets and lobes

One of the most powerful sites for the acceleration of UHECRs is the termination shock of gigantic lobes in radio galaxies. Of particular interest are a subclass of these objects known as Fanaroff-Riley class II objects (FR-II), that can in principle accelerate protons to $\sim 10^{20} - 10^{21}$ eV and explain the spectrum of UHECRs up to the GZK cutoff [43]. These objects are on average on cosmological distances. The accidental presence of a nearby source of FR-II type might explain the spectral shape above the GZK energy, but it would not be compatible with the observed anisotropy [44, 45]. Nevertheless, it has been recently proposed that a nearby source in the Virgo cluster (for instance M87)

and a suitable configuration of a magnetized wind around our own Galaxy might explain the spectrum and anisotropy at energies above $\sim 10^{20}$ eV [46] as measured by AGASA. This conclusion depends quite sensibly on the choice of the geometry of the magnetic field in the wind. Several additional tests to confirm or disprove this model need to be carried out.

4.2 The Top-Down Approach

An alternative to acceleration scenarios is to generate UHECRs by the decay of very massive particles. In these *particle physics inspired models* the problem of reaching the maximum energies is solved *by construction*. The spectra of the particles generated in the decay are typically flatter than the astrophysical ones and their composition at the production point is dominated by gamma rays, although propagation effects can change the ratio of gamma rays to protons. The gamma rays generated at distances larger than the absorption length produce a cascade at low energies (MeV-GeV) which represents a powerful tool to contrain TD models [47]. There are basically two ways of generating the very massive particles and make them decay at the present time: 1) trapping them inside topological defects; 2) making them quasi-stable (lifetime larger than the present age of the universe) in the early universe. We discuss these two possibilities separately in the next two sections.

4.2.1 Topological Defects

Symmetry breakings at particle physics level are responsible for the formation of cosmic topological defects (for a review see Ref. [48]). Topological defects as sources of UHECRs were first proposed in the pioneering work of Hill, Schramm and Walker [49]. The general idea is that the stability of the defect can be locally broken by different types of processes (see below): this results in the false vacuum, trapped within the defect, to fall into the true vacuum, so that the gauge bosons of the field trapped in the defect acquire a mass m_X and decay.

Several topological defects have been studied in the literature: ordinary strings [50], superconducting strings [49], bound states of magnetic monopoles [51, 52], networks of monopoles and strings [53], necklaces [54] and vortons [55]. Only strings and necklaces will be considered here, while a more extended discussion can be found in more detailed reviews [47, 56].

Ordinary strings

Strings can generate UHECRs with energy less than $m_X \sim \eta$ (the scale of symmetry breaking) if there are configurations in which microscopic or macroscopic portions of strings annihilate. It was shown [57, 58] that self-intersection events provide a flux of UHECRs which is much smaller than required. The same conclusion holds for intercommutation between strings.

The efficiency of the process can be enhanced by multiple loop fragmentation: as a nonintersecting closed loop oscillates and radiates its energy away, the loop configuration gradually changes. After the loop has lost a substantial part of its energy, it becomes likely to self-intersect and fragment into smaller and smaller loops, until the typical size of a loop becomes comparable with the string width η and the energy is radiated in the form of X-particles. Although the process of loop fragmentation is not well understood, some analytical approximations [56] show that appreciable UHECR fluxes imply utterly large gamma ray cascade fluxes (see however [47]).

Another way of liberating X-particles is through cusp annihilation [59], but the corresponding UHECR flux is far too low [60, 58] compared with observations.

The idea that long strings lose energy mainly through formation of closed loops was recently challenged in the simulations of Ref. [61], which show that the string can produce X-particles directly and that this process dominates over the generation of closed loops. This new picture was recently questioned in Refs. [62, 63].

Even if the results of Ref. [61] are correct however, they cannot solve the problem of UHECRs [56]: in fact the typical separation between two segments of a long string is comparable with the Hubble scale, so that UHECRs would be completely absorbed. If by accident a string is close to us (within a few tens Mpc) then the UHECR events would appear to come from a filamentary region of space, implying a large anisotropy which is not observed. Even if the UHECR particles do not reach us, the gamma ray cascade due to absorption of UHE gamma rays produced at large distances imposes limits on the efficiency of direct production of X-particles by strings.

Necklaces

Necklaces are formed when the following symmetry breaking pattern is realized: $G \to H \times U(1) \to H \times Z_2$. In this case each monopole gets attached

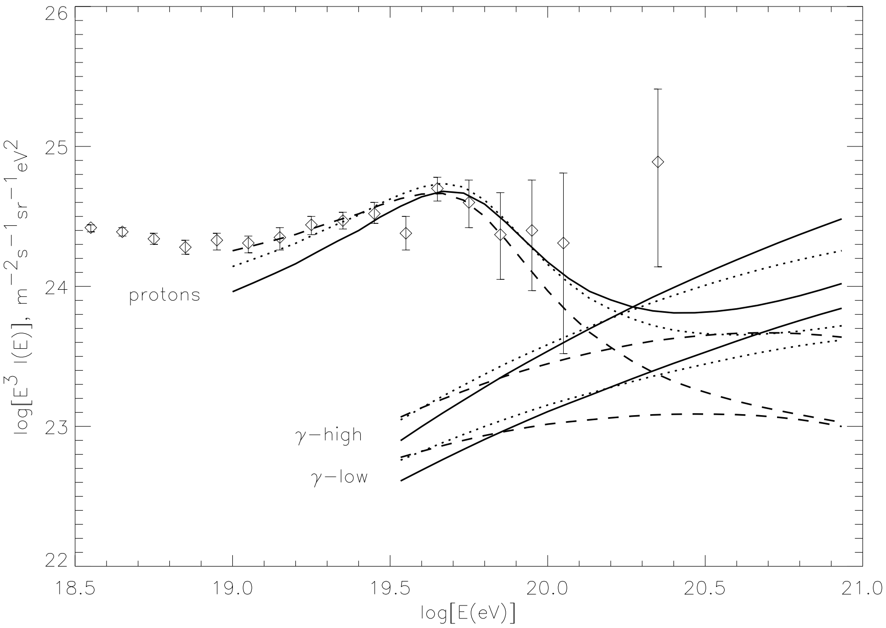

Figure 4: *Fluxes of UHECRs from necklaces* [56].

to two strings (necklace) [54]. The critical parameter that defines the dynamics of this network is the ratio $r = m/\mu d$ where m is the monopole mass and d is the typical separation between monopoles (e.g. the length of a string segment). If the system evolves toward a state where $r \gg 1$, the distance between the monopoles decreases and in the end the monopoles annihilate, with the production of X-particles and their decay to UHECRs. The rate of generation of X-particles is easily found to be $\dot{n}_X \sim r^2\mu/t^3 m_X$. The quantity $r^2\mu$ is upper limited by the cascade radiation, given by $\omega_{cas} = \frac{1}{2} f_\pi r^2 \mu = \frac{3}{4} f_\pi r^2 \mu / t_0^2$ ($f_\pi \sim 0.5 - 1$). The typical distance from the Earth at which the monopole-antimonopole annihilations occur is comparable with the typical separation between necklaces, $D \sim \left(\frac{3 f_\pi \mu}{4 t_0^2 \omega_{cas}}\right)^{1/4} > 10(\mu/10^6 GeV^2)^{1/4}$ kpc.

Clearly, necklaces provide an example in which the typical separation between defects is smaller than the pathlength of gamma rays and protons at ultra-high energies. Hence necklaces behave like a homogeneous distribution of sources, so that the proton component has the usual GZK cutoff. This component dominates the UHECR flux up to $\sim 10^{20}$ eV, while at higher energies gamma rays take over. The fluxes obtained in Ref. [56] are reported in Fig. 4, where the SUSY-QCD fragmentation functions [64] were used. The dashed

lines are for $m_X = 10^{14}$ GeV, the dotted lines for $m_X = 10^{15}$ GeV and the solid lines for $m_X = 10^{16}$ GeV. The two curves for gamma rays refer to two different assumptions about the radio background at low frequencies [65].

4.2.2 *Cosmological relic particles*

Super heavy particles with very long lifetime can be produced in the early universe and generate UHECRs at present [66, 68, 69, 70, 71]. In order to keep the same symbolism used in previous sections, we will call these particles X-particles.

The simplest mechanism of production of X-particles in the early universe is the *gravitational production* [72]: particles are produced naturally in a time variable gravitational field or indeed in a generic time variable classical field. In the gravitational case no additional coupling is required (all particles interact gravitationally). If the time variable field is the inflaton field ϕ, a direct coupling of the X-particles to ϕ is needed. In the gravitational production inflation is not required a priori, and indeed it reduces the effect. It can be shown that at time t, gravitational production can only generate X-particles with mass $m_X \leq H(t) \leq m_\phi$, where $H(t)$ is the Hubble constant and m_ϕ is the inflaton mass. The authors in Ref. [69] and [70] demostrated that the fraction of the critical mass contributed by X-particles with $m_X \sim 10^{13}$ GeV produced gravitationally may be $\Omega_X \sim 1$.

If the X-particles are directly coupled to the inflaton field, they can be effectively generated during preheating [73, 74]. Alternative mechanisms for the production of X-particles are based on non-equilibrium thermal generation during the preheating stage [66].

As mentioned in the beginning of this section, in order for X-particles to be useful dark matter candidates and generate UHECRs they need to be long lived (for a possible annihilation scenario see Ref. [67]). The gravitational coupling by itself induces a lifetime much shorter than the age of the universe for the range of masses which we are interested in. Therefore, in order to have long lifetimes, additional symmetries must be postulated: for instance discrete gauge symmetries can protect X-particles from decay, while being very weakly broken, perhaps by instanton effects [68]. These effects can allow decay times larger than the age of the universe, as shown in [75]. The slow decay of X-particles produces UHECRs. The interesting feature of this model is

that X-particles cluster in the galactic halo, as cold dark matter [56]. Hence UHECRs are expected to be produced locally, with no absorption, and as a consequence the observed spectra are nearly identical to the emission spectra, and therefore dominated by gamma rays. The very flat spectra and the gamma ray composition are two of the signatures. The calculations of the expected fluxes have been performed in [56, 76, 77, 78]. The strongest signature of the model is a slight anisotropy due to the asymmetric position of the sun in the Galaxy [79, 56, 80]. More recently a detailed evaluation of the amplitude and phase of the first harmonic has been carried out in [81] and [82]. The two papers agree that the present data is still consistent with the anisotropy expected in the model of X-particles in the halo. Small scale anisotropies do not find an easy explanation in TD models, with possibly the exception of the SH relics [83].

5 Hints of New Physics?

The possibility that at sufficiently high energies some deviations from known Physics may occur is of particular interest for UHECRs. Some attempts have been made to explain the events above 10^{20} eV as a manifestation of some kind of Physics beyond the Standard Model of particle interactions. These suggestions became even more interesting after the recent claims for correlations of the arrival directions of UHECRs with objects at large redshift. Some of these correlations are still subject of debate [84]. More recent studies result in a quite intriguing correlation with BL Lacs [85]. Two of the BL Lacs in the sample used in [85] are in the error box of the two triplets of events detected by AGASA, and correspond to a distance of ~ 600 Mpc, much larger than the pathlength for photopion production of protons (however more than half of the objects used in Ref. [85] have unknown redshift [Tkachev, private communication]).

The absence of bright nearby counterparts to the UHECR events has first inspired theoretical proposals of neutrinos as primary particles, since these particles are not affected by the presence of the CMB and can therefore propagate on cosmological distances without energy losses other than those due to the cosmic expansion. However, the small cross section of neutrinos makes them unlikely primaries: they simply fail to generate the observed showers in the atmosphere. There is one caveat in this argument: the neutrino nucleon cross

section at center of mass energies above the electroweak (EW) scale has not been measured, so that the argument above is based on the extrapolation of the known cross sections, and simply limited by the weak unitarity bound [86]. It has been proposed [87] that an increase in the number of degrees of freedom above the EW scale would imply the increase of the neutrino nucleon cross section above the standard model prediction. In particular, in the theories that predict unification of forces at ~ 1 TeV scale with large extra dimensions, introduced to solve the hierarchy problem [89], these additional degrees of freedom arise naturally, and imply a neutrino-nucleon cross section that increases linearly with energy, reaching hadronic levels for neutrino energies of $\sim 10^{20}$ eV (for string scale at 1 TeV). The calculations in Ref. [90] show that the cross section remains too small to explain vertical showers in the atmosphere (for possible upper limits on this cross section see Ref. [88]).

An alternative, even more radical proposal to avoid the prediction of a GZK cutoff in the flux of UHECRs consists in postulating a tiny violation of Lorentz invariance (LI). The main effect of this violation is that some processes may become kinematically forbidden [91]. In particular, photon-photon pair production and photopion production may be affected by LI violation. The absence of the GZK cutoff would then result from the fact that the threshold for photopion production disappears and the process becomes kinematically not allowed. It is suggestive that the possibility of a small violation of LI has also been proposed to explain the apparent absence of an absorption cutoff in the TeV gamma ray emission from Markarian-like objects [92] (see [93] for a critical view of this possibility).

6 Conclusions

The increasing evidence for a flux of UHECRs exceeding the theoretical expectations for extragalactic sources has fueled interest in several models. These models aim to satisfy all the requirements imposed by observations on fluxes, spatial anisotropies and composition. At present, however there is no obvious successful model. The situation might change with the availability, soon to come, of quite larger statistics of events, that will be achievable by experiments like the Pierre Auger Project [94] and EUSO/Airwatch/OWL [95, 96].

These future experimental efforts will be crucial mainly in three respects: 1) the increase of statistics by a factor 100 for Auger and even more for the

space based experiments will allow to strongly constrain theoretical models, and check whether the present excess is a $(2-3)\sigma$ fluctuation or a physical effect. Moreover the small scale anisotropies, if real, will become stronger and a correlation function approach will definitely become appropriate to the analysis of the events; 2) the full sky coverage will finally allow a test of models based on local extragalactic sources and on galactic sources of UHECRs, through the measurement of the large scale anisotropy, that is currently spoiled by the limited spatial exposure; 3) a better determination of the composition of the UHECR events will represent a smoking gun either in favour of or against models: TD models would be ruled out if no gamma rays are found or if heavy nuclei represent the main component. On the other hand, iron-dominated composition would point toward a possible galactic origin, possibly related to neutron stars.

The confirmation, on statistical grounds, of the association of UHECRs to distant cosmological objects like BL Lacs would represent a very strong indication of physics beyond the standard model. Either new interactions or some modification of fundamental physics would be needed to explain such a result.

References

1. K. Greisen, Phys. Rev. Lett. **16**, 748 (1966); G.T. Zatsepin and V.A. Kuzmin, Sov. Phys. JETP Lett. **4**, 78 (1966).

2. J. Linsley, Phys. Rev. Lett. **10**, 146 (1963).

3. M.A. Lawrence, R.J.O. Reid and A.A. Watson, J. Phys. G. Nucl. Part. Phys. **17**, 773 (1991).

4. N.N. Efimov *et al*: Ref. Proc. International Symposium on *Astrophysical Aspects of the most energetic cosmic rays*, eds M. Nagano and F. Takahara (World Scientific, Singapore), p. 20 (1991).

5. M. Teshima, proceedings of TAUP 2001, Laboratori Nazionali del Gran Sasso, L'Aquila, Sept. 8-12, 2001.

6. M. Takeda *et al* Astrophys. J. **522**, 225 (1999).

7. M. Takeda *et al*, Phys. Rev. Lett. **81**, 1163 (1998).

8. N. Hayashida *et al*, Phys. Rev. Lett. **73**, 3491 (1994).

9. D.J. Bird *et al*, Phys. Rev. Lett. **71**, 3401 (1993).

10. D.J. Bird *et al*, Astrophys. J. **424**, 491 (1994).

11. D.J. Bird *et al*, Astrophys. J. **441**, 144 (1995).

12. D. Kieda *et al*, *HiRes Collaboration* 1999 Proc. of 26th ICRC, Salt Lake City, Utah.

13. Y. Uchihori, M. Nagano, M. Takeda, M. Teshima, J. Lloyd-Evans and A.A. Watson, Astropart. Phys. **13**, 151 (2000).

14. T. Stanev, proceedings of the Vulcano Workshop "Frontier Objects in Astrophysics and Particle Physics", Vulcano, May 21-27, 2000.

15. F. Halzen, R. Vazques, T. Stanev and H.S. Vankov, Astropart. Phys. **3**, 151 (1995).

16. S. Yoshida and H. Dai, J. Phys. G **24**, 905 (1998).

17. M. Ave, J.A. Hinton, R.A. Vazquez, A.A. Watson, E. Zas Phys. Rev. Lett. **85**, 2244 (2000).

18. Numerous contributions have been presented by the HiRes Collaboration at the ICRC2001.

19. V. Berezinsky, A.Z. Gazizov, S.I. Grigorieva, preprint hep-ph/0107306.

20. M. Blanton, P. Blasi and A.V. Olinto, Astrop. Phys. **15**, 275 (2001).

21. V.S. Berezinsky and S.I. Grigorieva, A&A, **199**, 1 (1988).

22. T. Stanev *et al*, Phys. Rev. **D62**, 093005 (2000).

23. W. Saunders *et al*, preprint astro-ph/0001117.

24. J.P. Huchra, M.J. Geller and H.J. Corwin Jr., Astroph. J. **70** 687 (1995).

25. J.N. Bachall and E. Waxman, Astroph. J. **542**, 542 (2000).

26. N. Hayashida, et al., Appendix to Astroph. J. **522**, 225 (1999).

27. A.V. Olinto, Phys. Rep. **333**, 329 (2000).

28. R.D. Blandford, Phys. Scripta **T85**, 191 (2000).

29. A.M. Hillas, Ann. Rev. Astron. Astrop. **22**, 425 (1984).

30. E. Waxman, Phys. Rev. Lett. **75**, 386 (1995); ibid., Astroph. J. **452**, L1 (1995); M. Vietri, Astroph. J. **453**, 883 (1995).

31. A. Dar, preprint astro-ph/9901005; F.W. Stecker, Astropart. Phys. **14**, 207 (2000).

32. Berezinksy, V.S., Bulanov, S.V., Dogiel, V.A., Ginzburg, V.L., Ptuskin, V.S., *Astrophysics of Cosmic Rays* (Amsterdam: North Holland, 1990).

33. A. Venkatesan, M.C. Miller and A.V. Olinto, Astroph. J. **484**, 323 (1997).

34. P. Blasi, R.I. Epstein and A.V. Olinto, Astrophys. J. **533**, L123 (2000).

35. E.M. de Gouveia Dal Pino and A. Lazarian, Astrophys. J. **536**, L31 (2000)

36. M.C. Begelman, Astroph. J. **493**, 291 (1998).

37. J.H. Beall and W. Bednarek, preprint astro-ph/0108447.

38. J. Alvarez-Muniz, R. Engel and T. Stanev, in the proceedings of ICRC2001, OG1.03, Hamburg, Germany, 07-15 August 2001; S. O'Neill, A.V. Olinto and P. Blasi, in the proceedings of ICRC2001, OG1.03, Hamburg, Germany, 07-15 August 2001 (preprint astro-ph/0108401).

39. K.S. Thorne, R.M. Price, and D. MacDonalds, 1986 Black Holes: The Membrane Paradigm (New Haven: Yale Press) and references therein.

40. J. Magorrian *et al*, Astron. J. **115**, 2528 (1998).

41. E. Boldt and P. Ghosh, MNRAS **307**, 491 (1999).

42. A. Levinson, preprint hep-ph/0002020.

43. J.P. Rachen and P.L. Biermann, A& A **272**, 161 (1993).

44. G. Sigl, M. Lemoine and P.L. Biermann, Astropart. Phys. **10**, 141 (1999).

45. P. Blasi and A.V. Olinto, Phys. Rev. **D59**, 023001 (1999).

46. E.J. Ahn, P.L. Biermann, G. Medina-Tanco and T. Stanev, preprint astro-ph/9911123.

47. P. Bhattacharjee and G. Sigl, Phys. Rep. **327**, 109 (2000).

48. A. Vilenkin and E.P.S. Shellard, *Cosmic Strings and Other Topological Defects*, Cambridge University Press, Cambridge (1994).

49. C.T. Hill, D.N. Schramm and T.P. Walker, Phys. Rev. **D36**, 1007 (1987).

50. P. Bhattacharjee and N.C. Rana, Phys. Lett. **B246**, 365 (1990).

51. C.T. Hill, Nucl. Phys. **B224**, 469 (1983).

52. P. Bhattacharjee and G. Sigl, Phys. Rev. **D51**, 4079 (1995).

53. V.S. Berezinsky, X. Martin and A. Vilenkin, Phys. Rev. **D56**, 2024 (1997).

54. V.S. Berezinsky and A. Vilenkin, Phys. Rev. Lett. **79**, 5202 (1997).

55. L. Masperi and B. Silva, Astropart. Phys. **8**, 173 (1998).

56. V.S. Berezinsky, P. Blasi and A. Vilenkin, Phys. Rev. **D58**, 103515 (1998).

57. E.P.S. Shellard, Nucl. Phys. **B283**, 624 (1987).

58. A.J. Gill and T.W.B. Kibble, Phys. Rev. **D50**, 3660 (1994).

59. R. Brandenberger, Nucl. Phys. **B293**, 812 (1987).

60. P. Bhattacharjee, Phys. Rev. **D40**, 3968 (1989).

61. G. Vincent, N. Antunes and M. Hindmarsh, Phys. Rev. Lett. **80**, 2277 (1998).

62. J.N. Moore and E.P.S. Shellard, preprint astro-ph/9808336.

63. K. Olum and J.J. Blanco-Pillado, Phys. Rev. Lett. **84**, 4288 (2000).

64. V.S. Berezinsky and M. Kachelriess, Phys. Lett. **B434**, 61 (1998).

65. R.J. Protheroe and P.L. Biermann, Astropart. Phys. **6**, 45 (1996).

66. V.S. Berezinsky, M. Kachelriess and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997).

67. P. Blasi, R. Dick and E.W. Kolb, preprint astro-ph/0105232.

68. V.A. Kuzmin and V.A. Rubakov, Yadern. Fiz. **61**, 1122 (1998).

69. D.J.H. Chung, E.W. Kolb and A. Riotto, Phys. Rev. **D59**, 023501 (1998).

70. V.A. Kuzmin and I.I.Tkachev, JETP Lett. **69**, 271 (1998).

71. V.A. Kuzmin and I.I.Tkachev, Phys. Rep. **320**, 199 (1999).

72. Ya.B. Zeldovich and A.A Starobinsky, Soviet Phys. JETP **34**, 1159 (1972).

73. L. Kofman, A. Linde and A. Starobinsky, Phys. Rev. Lett. **73**, 3195 (1994).

74. G. Felder, L. Kofman and A. Linde, 1998 preprint astro-ph/9812289.

75. K. Hamaguchi, Y. Nomura and T. Yanagida, Phys. Rev. **D58**, 103503 (1998).

76. M. Birkel and S. Sarkar, Astropart. Phys. **9**, 297 (1998).

77. P. Blasi, Phys. Rev. **D60**, 023514 (1999).

78. S. Sarkar, 'COSMO-99, Third Intern. Workshop on Particle Physics and the Early Universe' pages 77-91, Trieste, 27 Sep-3 Oct 1999.

79. S.L. Dubovsky and P.G. Tynyakov, Pis'ma Zh. Eksp. Teor. Fiz. **68**, 99 [JETP Lett. **68**, 107] (1998).

80. W. Evans, F. Ferrer and S. Sarkar, preprint astro-ph/0103085.

81. V.S. Berezinsky and A. Mikhailov, Phys. Lett. **B449**, 237 (1999).

82. G.A. Medina-Tanco and A.A. Watson, Astropart. Phys. **12**, 25 (1999).

83. P. Blasi and R.K. Sheth, R.K., Phys. Lett. **B486**, 233 (2000).

84. G.R. Farrar and P.L. Biermann, Phys. Rev. Lett. **81**, 3579 (1998); C.M. Hoffman, Phys. Rev. Lett. **83**, 2471 (1999); G.R. Farrar and P.L. Biermann, Phys. Rev. Lett. **83**, 2472 (1999); G. Sigl *et al*, preprint astro-ph/0008363; A. Virmani *et al*, preprint astro-ph/0010235.

85. P.G. Tinyakov and I. I. Tkachev, preprint astro-ph/0102476

86. H. Goldberg and T. Weiler, Phys. Rev. **D59**, 113005 (1999).

87. G. Domokos and S. Kovesi-Domokos, Phys. Rev. Lett. **82**, 1366 (1999).

88. C. Tyler, A.V. Olinto and G. Sigl, Phys. Rev. **D63**, 055001 (2001).

89. N. Arkani-Hamed, S. Dimopoulos and G. Dvali, Phys. Rev. **D59**, 086004 (1999).

90. M. Kachelriess and M. Plumacher, Phys. Rev. **D62**, 103006 (2000).

91. S. Coleman and S.L. Glashow, Nucl. Phys. **B574**, 130 (2000); L. Gonzales-Mestres, Nucl. Phys. B (Proc. Suppl.) **48**, 131 (1996); R. Aloisio, P. Blasi, P. Ghia and A.F. Grillo, Phys. Rev. **D62**, 053010 (2000).

92. R.J. Protheroe, H. Meyer, Phys. Lett. **B493**, 1 (2000).

93. V.S. Berezinsky, preprint astro-ph/0107306.

94. J.W. Cronin, Nucl. Phys. B. (Proc. Suppl.) **28B**, 213 (1992).

95. See web page: http://www.ifcai.pa.cnr.it∼EUSO/home.html

96. R.E. Streitmatter, Proc. of *Workshop on Observing Giant Cosmic Air Showers from* $> 10^{20}$ *eV Particles from Space*, eds. Krizmanic, J.F., Ormes, J.F., and Streitmatter, R.E. (AIP Conference Proceedings 433, 1997).